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Regional application of ground source heat pump in China: A case of Shenyang

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ABSTRACT

Rapid industrialization, increasing population urbanization, and improved living standards have all contributed to greatly increasing greenhouse gas (GHG) emissions in urban areas of developing countries. This situation is especially true for China, where fossil fuel depletion is a critical issue from its contribution to GHG emissions, and in terms of resources being consumed. To address these issues the Chinese government has supported application of ground source heat pumps (GSHP) technology. This focus is meant to alleviate the dependence on fossil fuels and improve the country's energy structure. Several Chinese cities have embraced GSHP technology, and currently achieved some results. Shenyang, in Liaoning province, is one pioneering municipality. The city has become a champion of GSHP projects. However, the international energy research community has not been made aware of this important regional effort. The aim of this paper is to introduce and review the progress of GSHP technology diffusion within this region of China. This practical review will include policies, benefits and challenges facing the region and their adoption of GSHP technology. Recommendations for improvement of regional application on GSHP technologies given regional conditions are also made. These recommendations include strong leadership, appropriate policy incentives, effective enforcement mechanisms, and roundtable-based management. Relevant experience and lessons learned can be shared by other, globally locations, to help in GSHP technology diffusion.

Contents

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1. Introduction

China's rapid industrialization has caused many socio-economic and environmental challenges such as resource depletion, water pollution, sandstorms, soil erosion, deforestation, desertification, and recently, climate change [1,2]. In particular, China has doubled its emissions since the Kyoto protocol adoption in 1997. China is now the largest contributor of energy-related CO_2 emissions [3,4].

In response to these climate change concerns, the Chinese government has announced that China will reduce carbon dioxide emissions per unit of GDP by 40–45% in 2020 when compared to a 2005 baseline. They also have announced an increase of non-fossil fuels energy consumption to approximately 15% of all energy consumption by 2020 [5]. These voluntary actions are taken by the Chinese government because of national conditions and contributing to the global effort of tackling climate change concerns.

Concrete and practical action plans have been developed to practically achieve these targets. For instance, the National Development and Reform Committee (NDRC), a ministry level agency in charge of all planning issues in China, initiated the first national low carbon demonstration project in August 2010. Five provinces (Liaoning, Hubei, Yunnan, Shaanxi, and Guangdong) and eight cities (Baoding, Tianjin, Chongqing, Guiyang, Xiamen, Shenzhen, Nanchang, and Hangzhou) were chosen for pilot studies. These pilot studies are meant to aid government policy makers collect relevant experiences and lessons, and learn from implementation [6]. They will also facilitate development of a national regulations and standards to help promote the concept of low carbon development to various industrial sectors and regions.

A number of initiatives have been proposed for reducing CO_2 emissions in China. These initiatives include increasing forest carbon sinks, reducing the total consumption of fossil fuels, increasing the total consumption of renewable and clean energy (such as wind power, solar energy, geothermal energy, and natural gas), and increasing energy efficiency. Among these initiatives, the ground-source heat pump (GSHP) technology has been promoted by the Chinese Government as an effective geothermal energy technology.

A GSHP system is mainly comprised of a heat pump and a subsystem for ground heat exchange. GSHP systems utilize electricity, and less frequently gas, to operate their heat pumps. The ratio between output heat to supplied energy of GSHP is defined as the Coefficient of Performance (COP). A typical heat pump has a COP of around 4, indicating that the heat pump produces four units of heating energy for every unit of electrical energy input [7]. GSHP's major advantage is that it can substitute fossil fuel usage by using stored heat or cold that would otherwise be wasted.

GSHP systems are suitable for a wide variety of building types and are particularly appropriate for low environmental impact projects. They do not require hot rocks (geothermal energy), can be installed throughout many global regions using a borehole, shallow trenches or, by extracting heat from small bodies of water. Heat collecting pipes in a closed loop, containing water with a little antifreeze, are used to extract this stored energy. The energy can then be used to provide space heating and domestic hot water. In some applications, the pump can be reversed in summer for cooling purposes. Given these advantages, GSHP systems have been widely adopted throughout the world in such location as the UK [7], Germany [8], Korea [9], Poland [10], and Turkey [11].

China, with its vast territory and differentiated climatic zones, provides significant opportunities for the application of this technology, especially in colder regions such as Northeast China and Northwest China. In these regions winter heat demand is extreme with coal as the main energy source.

The first Chinese GSHP technology application occurred in the early 1980s, with increased promotion and adoption in the1990s [12]. Since that period several studies reviewing national GSHP adoption have been undertaken [12–14]. Currently, there is over140 million m^2 total building floor space energized by the GSHP technology. Over 80% of these projects are located in North or Northeast China.

The adoption of GSHP technology has resulted in an estimated CO_2 emission reduction of 22 million tons per year [14]. Detailed China-based case studies on individual buildings or projects, especially from a technical perspective, have also been conducted. For instance, studies have been performed on solar-ground source heat pumping systems with a vertical double-spiral coil (VDSC) ground heat exchanger (GHX) [15]; techno-economic comparisons of direct expansion ground sources and a secondary loop coupled heat pump systems for cooling in Chinese residential buildings [16]; design and installation of constant temperature and humidity air-conditioning systems driven by ground source heat pumps in Shanghai, [17]; and evaluation of shallow groundwater heat pumps performance in Beijing [18]. However, studies on how regional government can better promote the application of GSHP technology are rare, we have found no outstanding publication on this issue. This type of analysis is needed for investigation of appropriate management policies that can help in greater understanding and potential adoption of these technologies. Thus, this study is meant to address this gap and help build further policy knowledge associated with GSHP.

The city of Shenyang is selected as our case study region for several reasons. First, Shenyang is located in central Liaoning province in northeast China. On average this region is one of the coldest in China. A significant heat supply is needed in the cold of winter providing substantial potential demand for GSHP. Second, this city has been at the leading edge of GSHP adoption within China primarily due to robust support from local governmental officials. This governmental support was evident through financial subsidy programs and preferable zoning and building policies for facilitating the implementation of GSHP. Third, this city is also emblematic of continued rapid urbanization within China. It has major socio-economic conflicting forces at play from its situation as a modern city characteristics while being a refuge to a large poorly educated and recently urbanized (migrant) workforce. This microcosm of China offers a unique opportunity to further encourage the use of GSHP, if both demographic urban characteristics can function with this technology. Consequently, it is a good representation of most large cities in China and the experiences and lessons from this city can be shared and promoted in many other Chinese cities. By extension, many rapidly developing and emergent nations and their urban regions can learn from the study presented here.

In the next section we present an overview of the current GSHP practices in Shenyang. We then detail some of the major policies that promote regional application of GSHP. On the basis of this analysis, barriers and challenges are discussed. Finally, we provide our recommendations for further GSHP technology

diffusion throughout the regional level before drawing our conclusions.

The data and information sources in this paper include unpublished city government reports, published papers, and numerous interviews with key informants within the city. This triangulation of data sources ensures the credibility of our study. Information from city key informants was gathered through semi-structured interviews. Before these interviews several formal workshops and small group sessions were hosted by the authors. These sessions and workshops allowed for background discussion of the technology and the study. Thus interview session were completed with clearer answers and consistency with the objectives of the study. The whole investigation process was administered with the endorsement and support of the Shenyang Development and Reform Commission (SDRC). This support is needed to be able to overcome barriers associated with interviewing government officials in China. Local officials are apprehensive because they might feel that interview study results may be used as a basis for criticizing the local government. Consequently, such interviews represent a rare opportunity for examining the attitudes of various officials in Shenyang, as well as identifying the key barriers to GSHP management.

2. Current application of ground source heat pump (GSHP) in Shenyang

2.1. The social, economic and political context of Shenyang

Shenyang is located in central Liaoning province in northeast China (see Fig. 1 for details on Shenyang's location in China). This city has a total administrative area of 12,980 square kilometers and is composed by nine urban districts and four counties. Politically each urban district/county has their own government, but under the general administration of the Shenyang municipality.

In 2011 the population in Shenyang was 8.1 million people, and the GDP was 591.5 billion RMB (approximately 93.30 billion US dollars at a current exchange rate of 6.34 RMB/USD) [19]. Shenyang is one of China's largest industrial centers. It is home to an extensive industrial system including machinery, electronics, textiles, chemicals, metallurgy, and food industries. It is a key internal trading center in addition to its reputation as an industrial leader within China.

After China's reform and "opening" policies from the early 1980s, Shenyang has experienced rapid economic growth and urbanization. These socio-economic shifts have resulted in greater GHG emissions and energy consumption. Currently Shenyang is one of China's most prosperous commercial and distribution centers.

Weather conditions in Shenyang are typical for a northern city, with four seasons. Although Shenyang is known for its relatively lengthy winters and short summers. The average temperature in Shenyang ranges from $-12\ ^\circ C$ in January to $24.6\ ^\circ C$ in July [19]. The annual heating period in Shenyang is 152 days, indicating a need for significant amounts of energy consumption and greater CO_2 emissions. Most heat energy is provided by coal-burning boilers and co-generation power plants through district heating systems.

2.2. Development of GSHP in Shenyang

The first GSHP application in Shenyang was initiated in 2006, later than many other Chinese cities [20]. But its adoption has been very rapid since 2006. The Shenyang mayor has paid special attention to supporting the adoption initiative due to his strong belief that this technology can simultaneously help improve local air quality and reduce total coal consumption. In order to support its implementation, with his leadership, the city government established a special organization in September 2006, namely the Shenyang GSHP Promotion Office (SGSHPO). This office is part of the Shenyang municipal government and under the leadership of the city's construction commission (CC), a bureau level agency in charge of all building related issues.

The SGSHPO is politically superior to other departments within the CC because it is located organizationally higher up the government bureaucracy. The director of this office enjoys a vice directorship of the CC. The SGSHPO prepares policies, plans

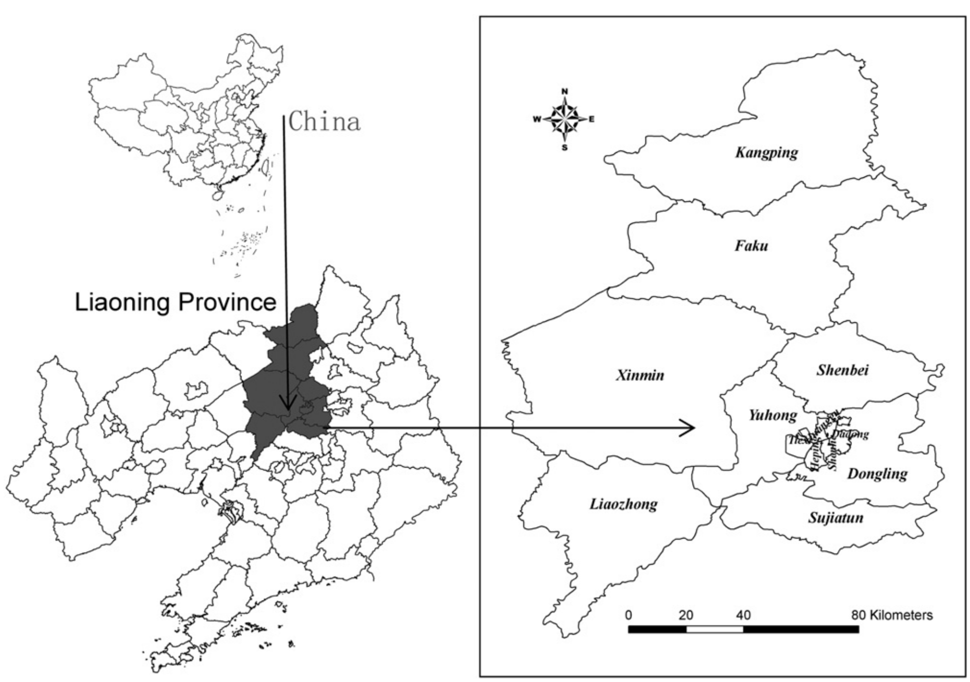

Fig. 1. Location of Shenyang city in China.

Table 1
Total projects and application floor areas of three types of GSHP in Shenyang (2007–2010).

	GCHP		GWHP		SWHP	
	Projects	Area 10^4 m^2	Projects	Area 10^4 m^2	Projects	Area 10^4 m^2
2007	18	270	192	1134.92	9	123.19
2008	13	302.9	147	813.99	11	501.6
2009	7	249.5	138	980.93	14	395.4
2010	0	0	121	852.62	1	3.85

the long term development of GSHP projects, manage all GSHP projects, provides technical support to GSHP users, manages economic subsidies to GSHP users, prepares technical standards and codes for the GSHP system, organizes publicity programs for promoting GSHP adoption, and fosters public sentiment to support governmental policies on GSHP. Significant effort by this office has helped grow adoption of GSHP in Shenyang to 59.41 million m^2 (780 projects). This amount represents 36.3% of all of China's implementation. It is the largest regional application of GSHP in China [20].

Significant benefits can be gained from the adoption of GSHP. Economically, the application of GSHP has certain advantages over traditional coal-burning based heating systems. Although materials, equipment, installation, operation and maintenance, and labor, cost also may vary across different regions, some benefits can be accrued economically. Our investigation with local officials in charge of GSHP issues indicates that the capital cost of GSHP system is on average100 RMB higher than the regular coal-burning heat system per square meter floor area. But the operation and maintenance cost is only 40% of a coal-burning heating system. Given that the yearly operation and maintenance cost for one square meter floor area through coal-burning heating system is 28 RMB/m^2, the 100 RMB initial investment premium can be paid back in 5.95 years ($100/(28\times0.6)=5.95$). Consequently, these relatively short returns-on-investment can be economically beneficial to developers and owners. In addition to general resource use reduction and carbon emissions benefits, another environmental and health benefit is total dust reduction of 2.04×10^4 t [20].

There are three types of GHSP implementation within Shenyang, namely, ground-coupled heat pump (GCHP), groundwater heat pump (GWHP), and surface water heat pump (SWHP, including sewage water heat pump) [20]. Table 1 summarizes the projects and application areas for each type of GSHP between 2007 and 2010.

2.3. Policies for supporting GSHP adoption in Shenyang

The Shenyang government has enacted several policies to promote GSHP adoption. Among the most important policies is a strategic development plan for GSHP in Shenyang. Understanding the local situation, needs and multi-stakeholder input were central to plan development. It clearly sets total floor area coverage targets for multiple years. Detailed geographical locations for technology implementation within the city territory have also been identified and prioritized. This process ensured that sub-governmental agencies, at urban district and county levels, are provided with clear direction for GSHP planning and promotion within their territories. The plan also clarifies governmental agency responsibilities. Within this agency responsibility identification agencies have been assigned various duties such developing financial mechanisms for supporting the initiatives, research and development, technological standards determination, and impact assessments. Moreover, the plan provides explicit guidelines for organizations wishing to do business in GSHP implementation to become qualified suppliers for making GSHP equipment. However, the plan only provides an overall framework for GSHP promotion and does not have any compulsory stipulations or legal authority. Therefore, several stringent policies were introduced to ensure that such a plan can be fully implemented.

One specific policy is "The implementation ordinance on fully promoting the application of GSHP in Shenyang" released in early 2006 [21]. The key aspect of this ordinance requires each urban district or county government within Shenyang to initiate a specified number of GSHP projects within their territory[1] . Thus, in order to fulfill this ordinance, leaders of local jurisdictions at the urban district or county level have to negotiate and agree to specific GSHP adoption targets for the next year. The Shenyang municipal authorities monitor progress at mid-year and evaluate results at year's end. A local leader failing to meet the targets for three consecutive years will not be eligible for promotion over the next five years. Consequently, this policy can provide strong political incentive for local leaders to support the GSHP adoption in their jurisdictions.

This ordinance also stipulates that all the GWHP projects have to guarantee groundwater replacement after extracting heat to avoid groundwater depletion and land subsidence issues. Organizations that do not comply with this regulation will be fined from 10,000 to 30,000 RMB (current exchange rate: 1 USD=6.34 RMB). Moreover, in order to ensure that the total amount of extracted groundwater can be measured, all the GWHP projects are required to be equipped with meters. Companies failing to include meters are fined from 5000 to 20,000 RMB [20]. The enforcement body of this ordinance is the head office of SGSHPO and its branch offices in all urban districts and counties.

Special financial incentives have been provided to encourage more participation in GSHP implementation. These incentives are primarily geared to partially reducing the cost of developing GSHP projects. For example, in order to promote GWHP projects, the extracted groundwater will not be charged, but just be measured so that the total amount is recorded. The electricity power price for operating GSHP facilities will be the same as the residential rate (e.g. 0.5 RMB/KWh), rather than normal commercial rate (e.g. 0.85 RMB/KWh) [21]. The city government convinced local banks to provide commercial loans to support those GSHP projects with a preferable interest rate (60% of normal interest rate) to alleviate the financial burden of businesses seeking to implement these projects.

Small GSHP projects can apply for grants from a special fund set up by the city government for energy saving and efficiency projects. Grants range in amount from 100,000 to 250,000 RMB and can be used for purchasing GSHP equipment and installation [20]. These funds are particularly helpful for small GSHP adopters who lack capital for adopting this technology. Without such financial mechanisms and a myopic focus on returns (looking for quick returns) many of them would likely choose the traditional coal-burning boilers for providing heating service to their users.

[1] Some background on China's public governance and control mechanisms is required here to help understand the policy execution process. To increase enforcement of localized regulations the State Council issued an order in 1996 requiring various levels of government to adopt an administrative leadership responsibility system. Thus, local government support for regulatory enforcement has improved in many locations. This was also reinforced by allowing Provincial governors, city mayors, and township heads to set up "ordinances" as a type of administrative measure. Under this system, key officials are evaluated annually by higher-level government officials. These higher level authorities can appoint, reappoint, and remove the officials based on a set of explicit performance indicators.

Another important policy is local regulation for administering commercial licenses for GSHP businesses. This policy requires that every company planning to operate within the GSHP 'industry', including GSHP equipment manufacturers, part suppliers for GSHP projects, GSHP equipment maintenance and repair service providers, has to meet the SGSHPO technical criteria and be regularly inspected by the local product quality supervision bureau (PQSB) and industry and commerce bureau (ICB). This policy mechanism helps ensure that only qualified companies are allowed to operate GSHP related businesses. This improves the quality products and services offered to consumers and companies seeking GSHP implementation. Only licensed companies can receive the financial benefits, because both financial subsidies and preferable tax rates can only be enjoyed by registered and licensed companies.

2.4. Evaluation of GHG emission reduction through the regional application of GSHP

In order to evaluate the greenhouse gas emission benefits of GSHP adoption in Shenyang, we utilize a life cycle assessment (LCA). LCA has been widely used to study the environmental burdens of energy produced from various renewable and non-renewable sources [22,23].

The initial step of an LCA is to determine a life cycle inventory (LCI). The LCI of GSHP projects includes all stages from project preparation to material production, manufacturing and transportation of GSHP related equipment, installation process, geothermal wells drilling, and grid electricity consumption in operation processes. However, due to lack of data, dismantling of the GSHP facility is not considered. In order to recognize the potential GHG emission, a base case is necessary, namely, providing heating and cooling service through traditional coal-burning boilers, the most popular technology in Shenyang. This base case assumes the average level of coal burning heat generation technologies currently operating in Shenyang.

The LCI of these two different energy options was established using different data sources including site specific data, published data, and published databases [24,25]. Life cycle GHG emission (LCE) was used as an index to evaluate the GHG emission characteristics of the two power generation technologies. The amount of greenhouse gases emitted across the entire life cycle to generate net 1 kWh of electricity is defined as follows:

$$LCE = \sum_i GWP_i \times \left(E_{f_i} + E_{c_i} + E_{o_i}\right)/Q \quad (1)$$

where E_f is direct emission caused by the combustion of coal in boilers. E_c is emission associated with the construction of facilities. E_o is emission for operation and maintenance of related facilities. E_c and E_o are here referred to as indirect emissions. Subscript i denotes the type of greenhouse gas (CO_2 and CH_4). GWP is the value of global warming potential factor of each greenhouse gas. Q is net output of electricity during a lifetime of related facilities. Net output is the amount of electricity supplied to the grid excluding the energy consumption for the operation of these facilities.

Only CO_2 and CH_4 emissions are considered as the greenhouse gases in this LCA study. CO_2 emissions are associated with the combustion of coal, while CH_4 emissions are associated with the leakage from the extraction of coal directly burned in boilers. The amount of CH_4 emissions was converted into CO_2 equivalents (CO_2-eq) using a global warming potential factor of 21.

CO_2emission associated with the energy requirement was calculated by multiplying the amount of energy with its CO_2 emission factor. The CO_2emission factor of coal was published by the Liaoning Provincial Research Institute for Coal Studies [26] and is used in this study. The CO_2 emission factor for electricity was calculated based on an average generation mix from the Northeast China grid.

CO_2 emissions associated with the construction of GSHP facilities are not easily calculated only from energy/materials inventories. The estimation of construction CO_2 emissions requires examining process chains relevant to the construction from resource extraction, materials production to manufacturing. However, detailed examinations of the process chains alone were not feasible due to data availability constraints. Therefore, in this study, a combined method of process analysis and input–output analysis was developed and employed. CO_2 emissions associated with materials (e.g. steel, aluminum) production were estimated by process analysis. Since available data regarding materials production are relatively abundant, the estimation by process analysis was feasible [26].

CO_2 emissions from various manufacturing processes (e.g. parts production, assembly) after accounting for materials production were estimated using an input–output analysis. Input–output analysis is a more efficient tool to analyze complex manufacturing processes considering the number and complexity of different products (e.g. boiler, turbine, pipe) required for power generation systems. With regard to environmental stressors strongly connected with coal combustion such as CO_2, the process of materials production was more important compared to other processes such as parts production and assembly. Therefore, the CO_2 emission from materials production was more accurately estimated using process analysis, while the CO_2 from other processes was roughly estimated using an input–output table.

Table 2 lists the GHG emission reductions from each of the three GSHP types from the period 2006–2010. Table 3 lists the total energy saving from the application of three GSHP types from the period 2006–2010. During the first five years of the GSHP government project initiation, and from a total investment of 10.69 billion RMB [20], 3.4 million tons of CO_2 equivalents (CO_2-e) had been reduced and the total energy savings were 109,856 TJ.

Since coal is the primary energy source in Shenyang and one ton of standard coal can produce 29.27 GJ energy means that 0.375 million tons of standard coal have been saved. Burning one ton of standard coal can generate 8.5 kg of SO_2 and 7.4 kg of NO_X [27]. This result means that the application of GSHP during 2006–2010 achievedSO_2 and NO_X reductions of 3187.5 and 2775 t,

Table 2
GHG emission reduction from GSHP application from 2006 to 2010.

	GCHP (10^4 ton)	GSHP (10^4 ton)	SWHP (10^4 ton)
2006	1.41	4.09	0.89
2007	4.47	26.20	6.15
2008	16.92	42.06	12.05
2009	26.74	61.17	16.91
2010	26.83	77.78	16.91
Sub-total	76.37	211.30	52.51

Table 3
Energy savings from GSHP projects during 2006–2010.

Year	GCHP (TJ)	GSHP (TJ)	SWHP (TJ)
2006	464.30	1639.25	356.41
2007	1471.01	10504.43	2465.46
2008	5570.11	16862.73	4831.50
2009	8801.33	24525.05	6780.41
2010	8832.80	31185.10	6780.41
Sub-total	25139.55	84716.56	21214.19

respectively. These reductions further contribute to significant environmental benefits.

Given that Shenyang's total building sector CO_2 emissions from 2007 was 16.27 million tons of CO_2-e [28], the savings from the GSHP project was about 4.18% of the CO_2 emission in Shenyang's building sector. Even comparing with the city's total CO_2-e emission in 2007 (57 million tons of CO_2-e) [28], such a saving was still about 1.2% of total CO_2-e emission. Therefore, GSHP implementation has contributed to the city's low carbon development effort.

3. Challenges

Although the city of Shenyang has made significant progress on promoting the GSHP adoption, several challenges still exist and need further study.

3.1. Technological challenges

Technological challenges can be categorized into several dimensions. In order to better develop GSHP projects at a regional level, it is necessary to fully understand the local hydrological and geological situation. These factors include water temperature, water quantity, water quality, soil components, porous medium, water flow rate, aquifer thickness, and ratio of permeability coefficient. This understanding requires a systematic inspection on the local situation before promoting GSHP projects. However, because of a lack of monitoring activities such data are not easily available for practitioners.

Many projects were initiated without a complete scientific analysis on relevant technological parameters and experienced significant technical difficulties. For instance, the limited availability of groundwater in some areas resulted in several projects inability to obtain enough groundwater for their operation. Several other projects suffered from facility corrosion their local groundwater's acidity.

Because Shenyang is located in a predominantly cold zone, heat pumps operate mainly in a heating mode. This mode results in gradual soil temperature decreases after a year's operation of the GSHP system. This decrease in temperature occurs because of inefficient recovery of soil temperature and imbalanced loads. This situation leads to negative environmental impacts on local flora which potentially threatens local biodiversity.

Another technological challenge is that many GSHP projects simply withdraw groundwater for heat exchange, without effective replacement or recharging of water. Economically it makes sense not to recharge wells since both drilling cost for recharging wells and the pumping and piping operational costs can be saved without recharging processes. Lack of recharging will result in land subsidence and groundwater depletion, increasing risks to the local ecosystem.

A lack of recharging causes heat buildup within the ground. This heat buildup increases the ground temperature, which can consequently deteriorate the system performance over time. To maintain efficient operating performance a larger ground heat exchanger (GHE) is always required. However, the high initial cost and large land area required for the larger GHE installation restricts wider adoption of GSHP technology in buildings with imbalanced loads.

GSHP projects at a regional level require optimal spatial plans. If two GSHP projects are geographically too close, then they may have interactive impacts and lower the heat transfer efficiency. In Shenyang many GSHP projects were initiated in 2009 and 2010 in urban areas and several projects were too close each other, resulting in these proximal difficulties [21].

3.2. Policy challenges

The second challenge is from a policy perspective. Several policies have been promulgated to promote the application of GSHP, but policy challenges still exist because the regional effort is still in its infancy. Although a financial subsidy mechanism was established to support such projects, this money is designated for hardware and installation costs only, not for the operation stage.

Diverse operational costs will occur given the different operational nature of various GSHP systems. As an example, sewage water heat pump projects require first removing pollutants from wastewater and frequent cleaning of pollutant-removing facilities. This operational situation increases both investment costs and operation and maintenance (O&M) costs. Although such projects enjoy the same financial policies and preferable tax rates as other GSHP projects, the long-term higher operational cost burdens have discouraged these companies from expansion.

The lack of policies encouraging broad public participation is another policy challenge. To date, GSHP projects have mainly been initiated by SGSHPO. This situation results in some potential enforcement issues. The official bureaucratic position of the SGSHPO is at the vice bureau level. This position means that the director of this office is the same as any vice directors of other bureaus. Given this organizational situation it is difficult for this office to enforce GSHP related regulations on other governmental units, especially those that are at higher hierarchical rankings.

The GSHP related policies and enforcement system are thus entirely dominated by the governmental agencies without any forum and provision for public participation or consultation. All decisions in the process are made solely by bureau officials. No institutional channels exist for the general public and those who are affected by the proposed projects to express their opinions. Without such public participation and genuine legislative oversight, it is difficult to ensure accountability in the project development process.

3.3. Operational challenges

The third challenge is the "implementation gap". The municipal government intentions are sometimes unrealized at lower levels, especially in dispersed rural areas where officials seldom inspect their operations. The GSHP related priorities, policies, and regulations of the Shenyang municipal government are modified at each interface as they cascade down through numerous urban districts, counties, townships, and villages. This modification is especially pronounced in rural Shenyang where the people are poor, the economy, local government, and local politics are tightly intertwined, and where guanxi and malleability still trump the law [29].

One example concerns enforcement at the township level. Although SGSHPO set up branch offices at the township level, typically with only a few full-time and part-time employees, they don't have authority to undertake direct enforcement. Only officials from the local construction commission are responsible for enforcement. This situation caused enforcement at the township level to frequently be subverted by township officials. These officials tip off relevant enterprises in advance of impending inspections.

Both the PQSB and ICB complained about insufficient personnel and financial resources for their inspections. Inspections are relatively new activities budgets are not sufficiently developed. They typically targeted urban areas for regular inspections. In addition, because of greater poverty in rural areas, lack of technical abilities, environmental awareness, and divergence of interests/priorities between city and lower level governments, the rural governments prefer to simply support the application of

cheap coal-burning or biomass based boilers and ignored their missions to promote GSHP projects.

4. Suggestions for improvement

The various challenges observed in Shenyang are very typical in China. Evidence of this similarity is documented in other, like studies [12–14,26,30]. Thus, providing suggestions to alleviate these challenges can benefit the implementation of GSHP projects in Shenyang and other locales.

4.1. Technologically-based recommendations

Probably the most important recommendation is for the Shenyang government should increase support for GSHP research and development (R&D) so that technological issues can be addressed. Since the city government has a yearly budget for supporting R&D activities through its Science and Technology Bureau (STB), it may be possible for STB to establish a special research grant on GSHP technologies so that local academic institutions can focus on developing specific technologies to meet local needs. If this type of localized research is not possible for some technologies, then the STB can help develop domestic and international partnerships.

Technological integration is needed as a single technology cannot function well. The GSHP system can be integrated with other heat sources to maintain a heat balance. Solar energy seems to be a promising technological partner. Theoretical and experimental studies, performed by Chinese researchers [15,31–34], promote the design and application of the solar assisted ground-source heat pump systems. Consequently, the combination of solar heater and GSHP could be one technical option in Shenyang.

Another R&D oriented solution example is to develop a hybrid system, namely, integrated soil cold storage and ground-source heat pump (ISCS and GSHP) system. Such a system may incorporate a supplemental heat rejecter/absorber to reduce the fair amount of heat rejected/extracted into/from the ground and then effectively balance the ground thermal loads.

A regular monitoring program can be set up to capture all the necessary technical parameters. A public information system can be developed so that those technical parameters can be shared through public websites or other channels. This information system can also collect and publicize the most updated GSHP related research outcomes, policies, and application progress both at home and abroad, ensuring that the activities and results of different research projects are effectively disseminated.

STB can create a technical forum on GSHP so that all the practitioners can exchange their expertise and experiences. Forums have been successful for promoting regional cleaner production activities because they create an opportunity for participants to exchange information and feedback, to obtain financial and personnel support, and to aid in negotiation [35].

4.2. Policy-based recommendations

Establishment of new and revisiting old policies is important. Liability legislation, requiring the polluter to compensate for environmental damage caused, provides a financial incentive for pollution prevention either direct costs or through insurance premiums.

Since GSHP implementation is a pollution prevention initiative, it seems reasons for the local government to set up a new regulation for ecological compensation. Such a regulation could stipulate that all development projects pay a certain amount of money for their development behavior. If environmental damage occurs due to their activities, they are responsible for improvements of an equal level, either directly or indirectly. Compared with traditional heating service providers, GSHP developers will have a significant financial advantage since they do not need to afford costs associated with ecological compensation for polluting activities (e.g. coal burning). Obviously this would not be an easy recommendation to implement, so careful investigation of alternative burden and economic shifting mechanisms may be considered, or implementation occur through careful incremental planning.

Another approach is to adopt economic instruments. Tradable permit is one potentially useful economic instrument to compensate for higher costs of GSHP projects. These permits may grant the right to pollute a specific amount, but may be sold to more polluting firms if not used. Historically, tradable permits for SO_2 emissions have proven effective for utilities in the United States [36] and can be expanded to CO_2 emissions. Setting up a CO_2 trading market will be necessary for GSHP developers to be able sell their credits to others. The credits they receive can be used to defray their expenditures on operation, thus, partially reducing their financial burden.

Public procurement is another way to support the dissemination of this technology. The government, as a standard bearer, can set a good example and may pave the way for cleaner products and technologies. Therefore, introducing policies requiring local governments to feasibly adopt GSHP technologies in their office buildings or other buildings receiving governmental funds, such as hospitals and schools, may be an effective and reasonable approach. Governmental agencies' resources will ensure greater adoption when compared with commercial development projects since investment hurdle rates are not as high for nonprofit-oriented government agencies.

4.3. Operationally-based recommendations

In order to address the implementation gap, several approaches can be pursued. One approach is to increase the capacity of SGSHPO to monitor enforcement at local levels. This requires an increased budget and more enforcement officials, as well as training for enforcement officials. Training programs are particularly important because it can improve officials' knowledge and awareness and to make sure that they meet the demands of effective and efficient enforcement.

Another approach is to inhibit other government agencies from undermining GSHP related regulatory enforcement. SGSHPO should coordinate and meet with other relevant government agencies, especially with PQSB, ICB and STB. Within these meetings they should discuss how to better coordinate enforcement issues, solve potential conflicts, monitor data, and prepare long term strategic planning on GSHP.

A third approach is roundtable-based management so that all the stakeholders can have their concerns on GSHP projects addressed. Roundtable-based management enables individuals, groups, and institutions to participate in identifying and resolving GSHP-related management issues. Members of this roundtable should cover all the relevant stakeholders so that each of them can express their opinions. This approach is based on the premise that involving stakeholders results in the production of relevant solutions that take into account each stakeholder's unique social, economic and environmental conditions and values. These roundtables are specifically aimed to help solve the issue of lack of public participation.

Roundtable-based management would be unique in China. Broad-based public participation in public affairs is still limited and weak. Therefore, further capacity building programs may be necessary so that all the stakeholders can improve their awareness and skills. Awareness-raising activities (including TV promotions, newsletters and regional symposia and workshops) should be used to build understanding, since such initiatives can provide forums at which experiences from different parts of the world and from

different institutions could be objectively reviewed and lessons drawn. These activities can also create opportunities for stakeholders to strengthen their mutual understandings, trust and respect, which will become a solid foundation for further collaboration. Ideally, these programs should be achieved through school programs, information sessions at the community level, print and electronic media, and brochures. Such a flexible and cooperative approach is more effective than a rigid, formalistic approach.

5. Conclusions

China is the largest greenhouse gas (GHG) emitter in the world and most GHG emissions come from urban areas. Alleviation of the total GHG emission in Chinese cities can be completed through renewable energy adoption. The GSHP technology adoption is one way to achieve this GHG reduction goal. It can also help restructure Chinese reliance on fossil fuels and should be actively promoted at the regional level. Shenyang is one pioneer in this regard and has become the top Chinese city for promoting GSHP adoption resulting in the largest floor area covered by this technology.

The reasons for Shenyang's successes and challenges have been described and analyzed in this paper. Such experiences and lessons can be shared and disseminated to other regions in China and in other developing regions of the world, so that more GSHP projects can be initiated and successfully operated. Success can be attributed strong leadership. Without senior officials' commitment, it will be hard to coordinate different stakeholders and make sure that the GSHP application can be supported through the institutional and bureaucratic framework of localized governments.

Second, a series of policies and regulations should be prepared with specific consideration of local situations. These policies should include financial incentives, appropriate regional plans, and effective and efficient enforcement mechanism, as well as broad public participation through roundtable based management.

Third, special attention should be paid to facilitate technological development. Due to its early stages in China, GSHP technological barriers exist and need to be solved through an integrated effort. Local government should set up a special research fund to support the related R&D activities and seek both domestic and international partnerships for the most effective solutions. With the implementation of these measures, regional government can significantly promote the application of GSHP systems and contribute to local low carbon development.

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References

[1] Geng Y, Doberstein B. Developing the circular economy in China: challenges and opportunities for achieving leapfrog development. International Journal of Sustainable Development and World Ecology 2008;15(3):231–9.
[2] Geng Y, Wang XB, Zhao HX, Zhu QH. Regional initiatives on promoting cleaner production in China: a case of Liaoning. Journal of Cleaner Production 2010;18:1500–6.
[3] Bosetti V, Carraro C, Tavoni M. Climate change mitigation strategies in fast-growing countries: the benefits of early action. Energy Economics 2009;31: S144–51.
[4] Guan DB, Liu Z, Geng Y, Lindner S, Hubacek K. The Gigatonne gap in China's CO2 inventories. Nature-Climate Change 2012;2:672–5.
[5] Geng Y. Eco-indicators: improve China's sustainability targets. Nature 2011;477:162.
[6] Geng Y, Sarkis J. Achieving national emission reduction target: China's new challenge and opportunity. Environmental Science and Technology 2012;46: 107–8.
[7] Omer AM. Ground-source heat pumps systems and applications. Renewable and Sustainable Energy Reviews 2008;12:344–71.
[8] Blum P, Campillo G, Kolbel T. Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany. Energy 2011;36: 3002–11.
[9] Lee J. Current status of ground source heat pumps in Korea. Renewable and Sustainable Energy Reviews 2009;13:1560–8.
[10] Paska J, Salek M, Surma T. Current status and perspectives of renewable energy sources in Poland. Renewable and Sustainable Energy Reviews 2009;13:142–54.
[11] Kaygusuz K, Kaygusuz A. Geothermal energy in Turkey: the sustainable future. Renewable and Sustainable Energy Reviews 2004;8:545–63.
[12] Yang W, Zhou J, Xu W, Zhang G. Current status of ground source heat pumps in China. Energy Policy 2010;38:323–32.
[13] Gao Q, Li M, Yu M, Spitler JD, Yan YY. Review of development from GSHP to UTES in China and other countries. Renewable and Sustainable Energy Reviews 2009;13:1383–94.
[14] Wang BJ. GSHP application in urban China and its future development trend. Heat Pump Newsletter 2011;7(1):11–3 [in Chinese].
[15] Bi Y, Guo T, Zhang L, Chen L. Solar and ground source heat pump system. Applied Energy 2004;78:231–45.
[16] Guo Y, Zhang G, Zhou J, Wu J, Shen W. A techno-economic comparison of a direct expansion ground source and a secondary loop ground coupled heat pump system for cooling in a residential building. Applied Thermal Engineering 2012;35:29–39.
[17] Yu X, Zhai XQ, Wang RZ. Design and performance of a constant temperature and humidity air-conditioning system driven by ground source heat pumps in Winter. Energy Conversion and Management 2010;51:2162–8.
[18] Laing J, Yang Q, Liu L, Li X. Modeling and performance evaluation of shallow ground water heat pumps in Beijing plain, China. Energy and Buildings 2011;43:3131–8.
[19] Shenyang Municipal Government. Shenyang Yearly Book 2011. Shenyang: Shenyang People's Publishing Group; 2012.
[20] Guo f. Application of GSHP technology and analysis on its recharge and capability in Shenyang urban area. Agriculture Science and Technology and Equipment 2011;200(2):97–9 [in Chinese].
[21] Shenyang Municipal Government. Shenyang twelfth five year plan on low carbon development, 2011–2015. Governmental report; 2011 [in Chinese].
[22] Hondo H. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 2005;30:2042–56.
[23] Ghafghazi S, Sowlati T, Sokhansanj S, Bi X, Melin S. Life cycle assessment of base–load heat sources for district heating system options. International Journal of Life Cycle Assessment 2011;16:212–23.
[24] Shenyang GSHP Administrative Office. Working report on promoting GSHP in Shenyang in 2010. Governmental report; 2011 [in Chinese].
[25] Shenyang GSHP Administrative Office. Technical handbook on GSHP systems. Shenyang: Shenyang Publishing Group; 2010 [in Chinese].
[26] Wang H. Exploration on the technical question of Shenyang groundwater environment heat pump (GRHP) system and its prospect. Ground Water 2009;31(6):154–6 [in Chinese].
[27] Tang Y, Zhang M. Summary of application of ground source heat pump in Shanghai. Low Temperature Architecture Technology 2011;157:110–2 [in Chinese].
[28] Xi FM, Geng Y, Chen XD, Zhang YS, Wang XB, Xue B, et al. Contributing to local policy making on GHG emission reduction through inventorying and attribution: A case study of Shenyang, China. Energy Policy 2011;39(2011):5999–6010.
[29] Tang SY, Lo CWH, Fryxell G. Enforcement styles, organizational commitment, and enforcement effectiveness: an empirical study of local environmental protection officials in urban China. Environment and Planning A 2003;35:75–94.
[30] Yu Y, Gu J, Luo JH. Brief discussion on ground source heat pump. Building Energy Efficiency 2010;38(235):32–3 [in Chinese].
[31] Yang Z, Zhao HB, Hu YF, Wu K. Research on annual performance factor of water–water heat pump system. Journal of Refrigeration 2006;27(3):24–9 [in Chinese].
[32] Wang HJ, Qi CY. Performance study of underground thermal storage in a solar–ground coupled heat pump system for residential buildings. Energy and Buildings 2008;40:1278–86.
[33] Wang HJ, Qi CY, Wang EJ, Zhao J. A case study of underground thermal storage in a solar–ground coupled heat pump system for residential buildings. Renewable Energy 2009;34:307–14.
[34] Han ZW, Zheng MY, Kong FH, Wang F, Li Z, Bai T. Numerical simulation of solar assisted ground-source heat pump heating system with latent heat energy storage in severely cold area. Applied Thermal Engineering 2008;28:1427–36.
[35] Geng Y, Wang XB, Zhao HX, Zhu QH. Regional initiatives on promoting cleaner production in China: a case of Liaoning. Journal of Cleaner Production 2010;18:1500–6.
[36] Hondo H. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 2005;30:2042–56.